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Phase-Coherent Astrometric Interferometry

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Phase-Coherent Astrometric Interferometry

The principal effort during the second year of this program involved continued development and use of the Mark III stellar interferometer. This is a fringe-tracking long-baseline Michelson interferometer designed primarily for wide angle astronomy at the milli-arcsecond level. Initial measurements of stellar diameters were also made, and it will be useful as part of a test bed for concepts relevant to aperture synthesis imaging. It is being constructed on Mount Wilson in California as a joint project involving the Massachusetts Institute of Technology, the Smithsonian Astrophysical Observatory, the Naval Research Laboratory, and the U.S. Naval Observatory. The first successful observations of 1986 were extended during 1987.

The two major instrument development efforts this year involve the laser siderostat subsystem and a real-time hardware autocorrelator designed to replace the fringe-tracking subsystem, and to permit operation with dimmer stars.

The laser metrology system was designed to measure motions of the siderostats, which reflect starlight into the interferometer, relative to the steel-reinforced concrete pedestals supporting the siderostats. The method implemented involved attaching a hemispheric mirror to the back of the main movable siderostat mirror such that the center of curvature for the hemisphere was located at the center surface of the mirror. Four laser interferometers measured the distance between the hemispheric mirror and an invar plate tied to the concrete pedestal. Measurements of distance at these four angles, separated by several tens of degrees, permit the location of the hemispheric mirror, and the attached siderostat mirror, to be measured quite precisely. This work was documented in the master's thesis "Laser Metrology System for Stellar Interferometer," submitted by B. E. Hines in January, 1988. The abstract for this thesis appears here as Appendix A.

The second project involved development of a new system to track fringes without requiring a high-speed mechanical subsystem. The method is implemented by taking the combined beam and spreading it into a thin line using a diffractive prism. This spectrum is then imaged in linear form on the face of a photon camera. If the interfering light beams are delayed properly, then all frequencies will simultaneously be in or out of phase. A delay in one beam introduces a quasi-sinusoidal modulation of intensity across the face of the photon camera. By measuring the spatial modulation characteristics of the spectrum, the position of the central fringe can be estimated on time scales of a few milliseconds.

Since mechanical tracking with fractional-wavelength accuracy is not required, this subsystem will in principle enable us to measure the positions of stars otherwise too dim to be measured with the traditional fringe-tracking approach. This work will constitute part of the master's thesis being prepared by Edward J. Kim. A more detailed description of his work during this time period follows.

During this period, the majority of the detailed design for the hardware autocorrelator was completed. Computation of the autocorrelation was implemented in hardware in order to meet the real-time speed requirements imposed by typical atmospheric coherence times (τ_o) at Mount Wilson. These requirements are to be able to compute and accumulate either a 256-point autocorrelation or the magnitude of a 256-point discrete Fourier transform every T milliseconds. T must be short compared to τ_o, and 4 ms was chosen as a minimum value for T. With accumulation also performed in real time, the remainder of the power spectrum computation (transforming or squaring) can be done on a more leisurely time scale.

The output of the PAPA detector consists of a series of addresses, one for every detected photon. Given input data in

this form, the autocorrelation can be computed using a simple photon-by-photon algorithm. In the low photon flux regime in which the group delay technique is expected to be used, this algorithm is more efficient than an FFT. It also requires no special-purpose IC's or microprocessors. The final correlator was constructed almost entirely with standard Fast TTL components. It incorporates approximately 140 IC's in a pipelined design with a 100 ns basic cycle time. The coherent integration interval can range from 4 ms to 16 ms, and the autocorrelations from as many as 4094 consecutive intervals are summed and saved in the accumulator memory in real time.

The correlator stores a time-ordered list of photon addresses during each coherent integration interval. The photon-by-photon algorithm operates by computing the address difference for all possible pairs of photons within each interval [see Figure 1]. Since the autocorrelation is symmetric, only half of all possible pairings need to be used, and computation time is halved [e.g., upper triangle only].

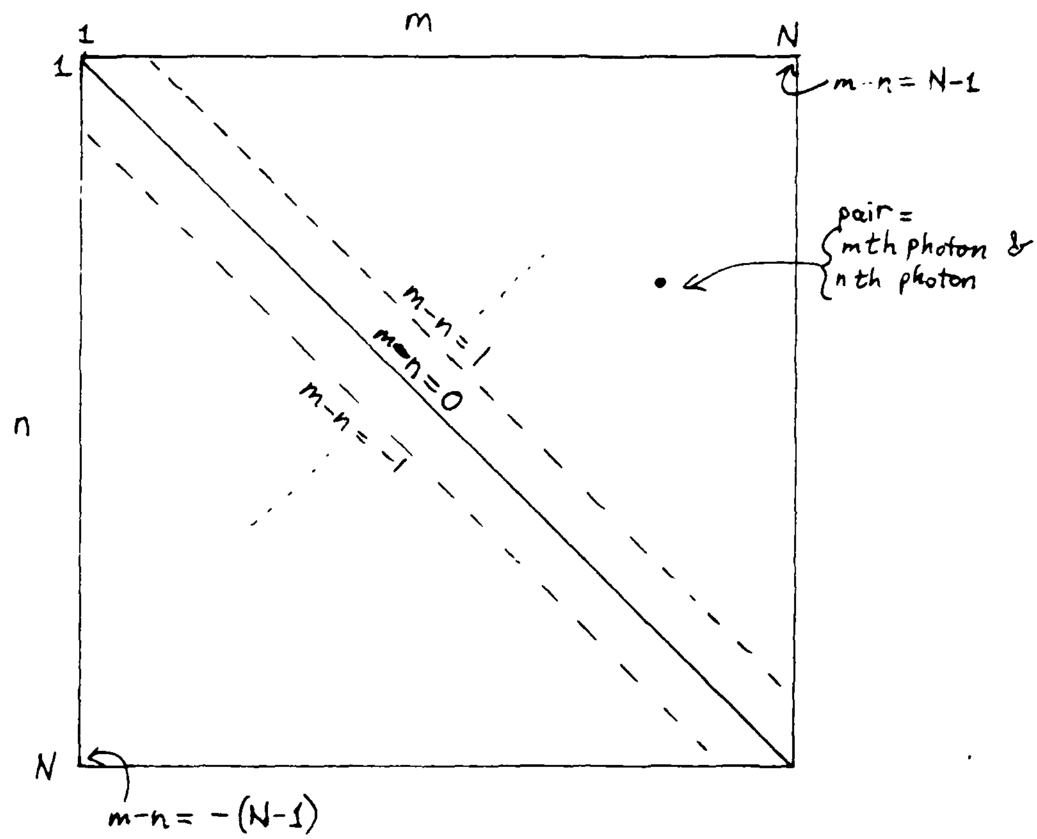
The pairings corresponding to the diagonal [m = n] represent the correlation of each photon with itself. These self-correlations do not give us any information about the position of a photon arrival along the spectrum strip (i..e, frequency or wavelength) since they only contribute to the zero lag value. In the power spectrum domain, this photon noise bias hampers certain aspects of the data analysis unless it is removed. It can be removed in the correlator by simply not computing the pairs along the diagonal. This is not currently done, but the necessary modification to the correlator is known and is not too complex.

The most timing-critical part of the design utilizes sub-100 ns timing, and there was uncertainty as to whether all the components involved would cooperate to the necessary extent. This part was therefore constructed first and thoroughly tested before construction of the rest of the correlator

proceeded. By February, 1988, between one-half and two-thirds of the hardware construction was complete.

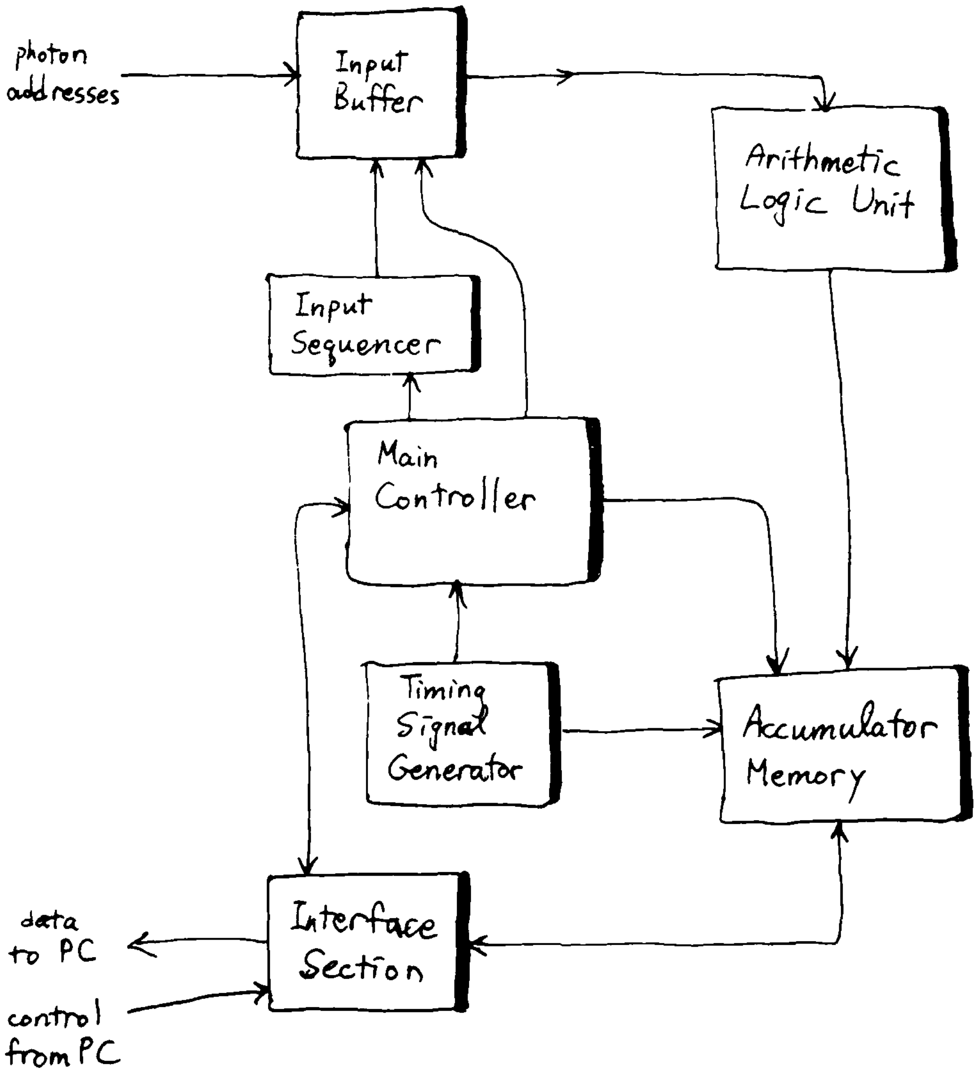
Figure 2 is a block diagram of the correlator. A PC was configured to generate control signals and fake data for the testing of each section of the correlator hardware. Sections were first tested in isolation, then when interconnected. In this manner, the entire correlator was eventually tested, all under PC control. The PC also proved extremely useful for the storing and modifying of the correlator schematics. A commercial CAD package was employed.

Figure 1



Photon-Photon pairs.
Computation diagram for N photons

Figure 2



Correlator Block Diagram

APPENDIX A

LASER METROLOGY SYSTEM FOR STELLAR INTERFEROMETRY

by

Braden E. Hines

Submitted to the Department of Electrical Engineering and Computer Science on January 15, 1988 in partial fulfillment of the requirements for the Degree of Master of Science in Electrical Engineering.

ABSTRACT

Optical interferometry promises to produce astrometric measurements of unparalleled accuracy. However, since optical interferometry by its very nature pushes against the frontiers of many different technologies at once, sophisticated and highly accurate systems are needed to monitor many aspects of the instrument's performance. This thesis is concerned with one such system, a laser metrology system designed to measure motions of the siderostats which reflect starlight into the interferometer optics.

As the siderostats sweep the sky to point at and track different stars, the surface of the siderostat mirror, unfortunately, does not pivot about a fixed point. There are a number of imperfections in the siderostats; among them are irregularities in the bearings and gears of the siderostats, noticeable backlash in the gears, and nonintersection of the two axes of rotation. In the Mark III Interferometer at Mt. Wilson Observatory, the siderostats have been designed in such a way as to accommodate the placement of a *laser plate* beneath the siderostat mirror. This laser plate consists of five laser interferometers, four of which are pointed at the siderostat mirror. These laser interferometers are used to measure the motion of the surface of the siderostat mirror; knowledge of this motion then allows computation of a correction to the measured fringe position for the star, reducing the residual errors after solving for the baseline. Without the laser plate, errors on the order of 5-20 microns in fringe position can occur.

A laser plate system was installed and tested at Mt. Wilson to determine the resultant reduction in the residuals. Hardware was designed and built to allow a computer to read the values measured by the laser interferometers to an accuracy of $\lambda/64$, where λ equals 633 nm. Software was implemented to record the data in real time, process the raw data, solve for the laser plate model, convert the laser readings to mirror motion, and, lastly, convert mirror motion into changes in fringe position. The system was tested and debugged at Mt. Wilson, and data is presented which illustrates the function of the system. This thesis describes the design and testing of the laser metrology system.

The Mark III interferometer is a joint effort of the Massachusetts Institute of Technology, the Harvard/Smithsonian Astronomical Observatory, the United States Naval Observatory, and the Naval Research Laboratory.

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